

The Discovery of Balmer-filaments Encircling SNR RCW 86

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ABSTRACT

We report the discovery of Balmer-dominated filaments along almost the complete periphery of the supernova remnant RCW 86 (also known as G 315.2-2.3 or MSH 14-63). Using the UM/CTIO Curtis Schmidt telescope, we obtained deep CCD images in the emission of $H\alpha$ and $[S\ II]$, together with continuum images to remove stellar confusion. After continuum subtraction, we discovered a network of $H\alpha$ filaments reaching almost completely around the remnant. Most of the newly identified filaments show no corresponding $[S\ II]$ emission, indicating that they belong to the peculiar “Balmer-dominated” class of filaments. Comparison of these Balmer filaments with existing radio and X-ray images of RCW 86 shows an overall similarity, although interesting differences are apparent upon detailed inspection. While further observations of these newly identified optical filaments may eventually provide more detailed information on the kinematics and distance to RCW 86, the distance currently remains uncertain. We argue that the shorter distance estimates of ~ 1 kpc are still favored.

Subject headings: supernova remnants: individual (RCW 86) — ISM: individual (RCW 86) — nebulae: individual (RCW 86) — shock waves — supernovae: individual (SN 185)

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1. Introduction

The supernova remnant RCW 86 (also known as MSH 14-63, G 315.4-2.3, PKS 1439-62) has received much attention in recent years. It is among the brightest supernova remnants (SNRs) in X-rays in our Galaxy, and shows up as a bright non-thermal shell in the radio. Perhaps more interesting, though, is that it has been identified as the the possible remnant of the supernova of A.D. 185, the first historical report of a Galactic supernova (Clark & Stevenson 1977). However, the relation between the supernova and this remnant has been called into question recently (e.g., Huang & Moriarty-Schieven 1987 and Thorsett 1992), and indeed the nature of the recorded event has also been questioned (Chin & Huang 1994, Schaefer 1995). Much of the debate revolves around the distance to the supernova remnant, with values which range from <1 to 3 kpc, and whether the event of A.D. 185 was a Type Ia or Type II supernova, if it was in fact a supernova! But the connection between the observations of a bright object in A.D. 185 and the SNR RCW 86 remains an intriguing possibility which, if confirmed, would provide an exact age for the remnant, making it the oldest SNR with a known age and allowing for more detailed modeling and a better understanding of its evolution.

The SNR RCW 86 is a bright, almost complete shell in both radio and X-rays. The radio shell was identified in the MSH survey (Mills, Slee, & Hill 1961) and soon after found to be a non-thermal and polarized source (Hill 1964, 1967), indicating that it was in fact a supernova remnant. Later higher resolution radio work (e.g., Kesteven & Caswell 1987) showed that the remnant is a roughly circular shell, approximately $40'$ in diameter, with a bright knot in the southwest. Distance estimates based on the radio Σ -D relation (e.g., Clark & Caswell 1976, Ilovaisky & Lequeux 1972, Milne 1970) gave 2.0–3.2 kpc. While the Σ -D relation has been shown to be notoriously unreliable (Green 1991), many of the distances which continue to be quoted in the SNR literature are based on these estimates.

The first X-ray observations of RCW 86 were obtained by Naranan et al. (1977), who interpreted the 0.5-2.5 keV X-ray spectrum as thermal bremsstrahlung radiation with a temperature of ~ 0.4 keV. The *Einstein Observatory* provided the first spatially resolved X-ray maps of the remnant (Pisarski, Helfand, & Kahn 1984). The IPC observations showed a limb-brightened shell in general agreement with the overall radio structure, though significant detailed differences were apparent. Both IPC and HRI observations of the southwest portion of the remnant showed a bright knot (or knee, as resolved in the HRI observation), roughly matching the bright radio emission from that region. Analysis of the *Einstein Observatory* dataset and subsequent X-ray observations (Claas et al. 1989, Kaastra et al. 1992) have all agreed on distances of between 0.7 and 1.3 kpc *assuming* an age of ~ 1800 years, i.e., that the remnant is that of SN 185.

While the remnant is a roughly circular shell with a bright knee in the SW in both radio and X-rays, the previously known optical emission was confined to a complex of bright filaments in the southwest, a couple of knots of optical emission to the west of the center, and a few additional short

filaments along the northern edge of the radio/X-ray remnant. Actually, the original designation “RCW 86” referred specifically to the bright optical nebulosity identified by Rodgers, Campbell, & Whiteoak (1960) in the southwest of the remnant, filaments which correspond to the brightest radio and X-ray structures. However, herein we use the designation RCW 86 to refer to the whole SNR, as is now common in the literature. Although the relation of the two knots and northern filaments to the remnant was noted as long ago as 1967 (Hill 1967), almost all optical studies of the remnant have concentrated on only the bright filaments in the southwest. Westerlund & Mathewson (1966) established that these optical filaments showed strong $[\text{S II}] \lambda 6724$ emission, a common characteristic of SNR filaments. Later spectroscopy (Ruiz 1981, Leibowitz & Danziger) confirmed that the emission from the southwestern nebulosity was consistent with that calculated from models of radiative shock emission.

More recently, Long & Blair (1990) discovered a different type of filaments, so-called Balmer-dominated filaments, in the southern edge of the bright southwestern complex and also among the northern filaments. Balmer-dominated filaments are distinguished by a spectrum of Balmer lines with little or none of the forbidden-line emission (such as $[\text{S II}]$, $[\text{N II}]$, and $[\text{O III}]$) that characterizes the radiative filaments typical of most supernova remnants. Such Balmer-dominated filaments arise from relatively high velocity shocks passing through low-density, partially neutral gas, producing a collisionless shock front. Neutral atoms (mostly hydrogen) stream through the shock front into the hot postshock medium, where they are almost immediately ionized. However, there is a small probability that the atoms are excited and emit before being ionized, producing the faint Balmer filaments seen in a small minority of remnants. Such filaments define the Balmer-dominated class of SNRs, which includes SN 1006, Tycho, and four remnants in the LMC (Smith et al. 1991 and references therein). Balmer-dominated filaments have also been observed in Kepler’s SNR (Fesen et al. 1989) and along the outer edges of the Cygnus Loop (Raymond et al. 1983, Hester, Raymond, & Danielson 1986). While the radiative filaments typical of evolved SNRs represent gas in the cooling zones behind the shock front, these Balmer-dominated filaments are produced at the leading edge of the shock, where the gas is in the process of being ionized. Hence these Balmer filaments trace the actual shock front as it moves into the ambient interstellar medium.

Here we report the discovery of a complex network of Balmer-dominated filaments stretching around almost the complete periphery of RCW 86. These newly identified filaments provide a detailed, high-resolution optical tracer of the blast-wave shock front, and offer opportunities to better understand the remnant and its possible progenitor. In §2, we present the observations and reductions, and in §3 we go on to describe the newly identified optical filaments. In §4 we compare the optical outline of the SNR with the morphologies in both the radio and X-rays. A summary is given §5, together with a review of the current debate over the distance to and possible progenitor of SNR RCW 86.

2. Observations & Reductions

The narrow-band optical images of RCW 86 were taken with the CCD camera attached to the Newtonian focus of the 0.6/0.9m UM/CTIO Curtis Schmidt telescope during two separate observing runs, 1994 March 23-24 and 1995 January 26-29 UT. For both runs, the detector was a Thomson 1024×1024 CCD with 19 μ m pixels, providing a scale of 1".835 pixel⁻¹ and a field of view of 31'.3. The resulting FWHM resolution for the observations averaged ~ 1.8 pixels or $\sim 3''$. Narrow bandpass filters of H α ($\lambda_c = 6563$ Å, FWHM = 26 Å) and [S II] ($\lambda_c = 6718$ Å, FWHM = 50 Å) were used to isolate the nebular emission. In addition, a “red continuum” filter ($\lambda_c = 6844$ Å, FWHM = 93 Å) was used to obtain images free from emission lines, to allow for accurate subtraction of stars from the emission-line images.

Since the field of view was smaller than the $\sim 40'$ diameter of RCW 86, a rough grid of four fields was used to cover the area of the remnant, with one additional field near the center for improved signal-to-noise in the center and more accurate image alignment. Multiple images with small offsets were taken through each filter at each pointing. A summary of the observations is provided in Table 1. Images of several spectrophotometric standards (Hamuy et al. 1992) were obtained to provide absolute flux calibration for the emission-line images.

The images were reduced using standard IRAF³ tasks for zero correction, bias subtraction, and flat-fielding with twilight sky flats. The images were then combined into mosaics using IRAF’s `geotrans` routine and a procedure similar to that described by Winkler, Olinger, & Westerbeke (1993). This involved identifying several (~ 10) stars with known positions (from the *HST* Guide Star Catalog) in each image and then mapping the images individually into “canvases” the size of the final image. These canvases were then combined to produce the final H α , [S II] and red continuum mosaics. The resulting H α mosaic image is shown in Fig. 1 (Plate XX).

To remove the stellar confusion, ~ 100 stars from the mosaic of images taken in the red continuum filter were measured and compared to the stars in the H α and [S II] mosaics. The red mosaic was then scaled by the resulting average flux ratio and subtracted from each emission-line mosaic. The resulting continuum-subtracted H α mosaic is presented in Fig. 2 (Plate XX). To help remove the remains of subtracted stars, the emission-line mosaics were median filtered with a 5×5 pixel (9" square) kernel. The final median-filtered H α and [S II] mosaics are shown in Figures 3 (Plate XX) and 4 (Plate XX), respectively. The H α mosaic has an average per pixel exposure time of ~ 5400 s (not counting the center, where the exposure is much deeper due to the overlap of the fields), while the average [S II] exposure time per pixel is ~ 1900 s. In the continuum-subtracted H α image, which is the image we use to measure surface brightnesses, the background rms noise is approximately 1.2×10^{-17} ergs cm⁻² s⁻¹ arcsec⁻² (not including bad stellar subtractions). This pixel-to-pixel noise, however, provides only a conservative surface brightness limit estimate for our

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H α image, since large-scale features covering many pixels even at that limit will be easily visible.

3. Optical Morphology of RCW 86

The final continuum-subtracted H α mosaic image is reproduced in Fig. 5 with the principal filaments and filament complexes labeled. The filament complexes have been numbered from the geometric center of the remnant outward, so that smaller numbers indicate smaller projected distance from the center, and a suffix “b” or “r” has been added to indicate Balmer-dominated and radiative filaments, respectively. Where there is a mix of radiative and Balmer-dominated filaments, we leave off the suffix unless we are speaking specifically of one or the other. In lieu of spectroscopic information, the filaments which show no [S II] counterparts in Fig. 4 are considered Balmer-dominated. While the [S II] mosaic is not as deep as the H α mosaic, our [S II] images are nevertheless sensitive enough to identify filaments with a [S II]/H α ratio of ≥ 0.4 , characteristic of radiative shock emission, for all of the H α filaments discussed herein.

It is immediately apparent that these newly discovered Balmer-dominated filaments, stretching almost all the way around the periphery of RCW 86, provide a much more complete picture of the remnant than do the radiative filaments. Indeed, even at the relatively coarse resolution of $3''$, the H α mosaic provides the highest resolution image of the complete shell of RCW 86 available at any wavelength to date. The west and east sides are well defined, giving the remnant a somewhat boxy appearance, with only the southeastern corner showing little detectable optical emission.

As shown by Long & Blair (1990), Balmer-dominated filaments are intermingled with radiative filaments in the edges of SW1 (the original RCW 86 nebula). The previously identified filaments are some of the brightest Balmer-dominated filaments of the whole remnant, with surface brightnesses of up to $\sim 3.0 \times 10^{-16}$ ergs cm $^{-2}$ s $^{-1}$ arcsec $^{-2}$. Additional fainter Balmer filaments (S1b) are seen extending to the east of the bright nebula, tracing out at least part of the southern portion of the remnant.

Along the northern side, we see that the filaments break up into two separate, almost parallel, complexes. Long & Blair identified the Balmer filaments mixed in with the radiative filaments along the inner set of northern filaments, N1. To the north of this mixture are several knots of emission, which we label N2. Given the apparent leading position of this outer set of filaments, there are surprisingly few Balmer filaments detected among the radiative filaments. Some of the filaments seem to be Balmer-dominated at one end and radiative at the other, perhaps implying a recent interaction of the remnant shock front with dense clumps of matter.

The filaments of the N1 complex can be followed down the east side along a very faint, somewhat diffuse filament which brightens and sharpens into E2b, the outer of the eastern filaments. The E2b complex is actually two or three parallel filaments with faint Balmer emission filling the area between them. To the interior is the fainter E1b filament. Since Balmer-dominated filaments trace the blast wave shock front, where neutral gas is being ionized, E1b’s interior

position is most likely only the result of projection. It probably represents a ripple along the front or back face of the remnant shell. A similar argument might be made for the inner filament along the northern rim, N1, but the broken structure and lack of many Balmer filaments in N2 implies that the situation is probably more complex there.

The peculiar emission-line profile which characterizes Balmer-dominated filaments may provide a key to deciphering the three-dimensional geometry of these shocks. The $H\alpha$ line profile from these collisionless shocks consists of two components (Chevalier & Raymond 1978, Chevalier, Kirshner, & Raymond 1980, Kirshner, Winkler, & Chevalier 1987, Smith et al. 1991). A narrow component is produced as neutral H atoms stream through the shock front and are excited in the hot post-shock medium *before* they are ionized and accelerated to the post-shock velocity distribution. The line profile from these “slow neutrals” is therefore characteristic of the pre-shock conditions, and typically has a FWHM of $\sim 30 \text{ km s}^{-1}$ (Smith, Laming, & Raymond 1994) and a line center corresponding to the rest velocity of the pre-shock gas. The second component is a broad feature created by fast ions which undergo charge exchange with the slow neutrals, producing “fast neutrals” which have a small probability of being excited and emitting before being ionized. This broad component has a FWHM proportional to the shock velocity and a line center which is determined by the combination of the bulk flow of the post-shock gas and the angle to the line of sight. The offset between the narrow-component line center and that of the broad component is therefore the component of the post-shock flow along our line of sight. Given that we can determine the velocity of the post-shock flow from the width of the broad component, we can derive the angle to the line of sight for any filament which shows an offset between the line centers of the broad and narrow components. The offset measured by Long & Blair (1990) of 1.4 \AA in the N1b filaments translates to an angle to our line of sight of approximately 84° . Assuming an approximately spherical shell, this places those filaments in a position on back face of the shell about 6° behind the plane of the sky. Similar measurements should allow us to determine the relative positions of the E1b and E2b filaments.

The west side of the remnant exhibits a far more complex structure, with three distinct filament complexes. The W3b filament complex seems to mark the projected outer extent of the remnant, where the shock is presumably close to perpendicular to our line of sight. It is made up of many short filaments, a few of which are at large angles to the average curve, creating a small triangular structure in the west-northwest. The W2b filament complex, the brightest of the three structures, is much more uniform, consisting of several long, thin filaments. These are again presumably ripples either in the front or back shell of the remnant.

The whole area of the western filaments is filled with a faint diffuse component, with the W1b filaments marking the inner edge of this diffuse emission. If we assume that this emission is from the uniform surface of the shell between W2b and W1b, the $H\alpha$ intensity provides a first order method to estimate the neutral ambient density, n_{HI} . Using the relation given in Winkler & Long (1997, eq. 2), which is based upon the Chevalier & Raymond (1978) derivation of 0.048

H α photons per H atom passing through the shock, we find that

$$I_{\perp} = 0.23 \times 10^{-16} n_{HI} (v_s/800 \text{ km s}^{-1}) \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ arcsec}^{-2}.$$

Measuring the surface brightness midway between W1b and W2b, at a projected radius of approximately $R/R_{SNR} = 0.7$, the intensity should be approximately $I = 3 \times I_{\perp}$ (assuming a line of sight passing through a thin spherical shell, $\Delta R/R < 0.01$). The measured surface brightness of $6 \times 10^{-17} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ arcsec}^{-2}$, together with the shock velocity of 800 km s^{-1} measured in N1 (from Long & Blair 1990) gives us an estimate of $n_{HI} \approx 0.9 \text{ cm}^{-3}$, which is slightly higher than than found in either Tycho’s SNR (Kirshner, Winkler, & Chevalier 1987) or SN 1006 (Winkler & Long 1997). This is of course only a rough estimate. With detailed spectroscopy, resulting in measurements of the broad and narrow component line centers and an estimate of the shock velocity at the same location, we should be able to determine the geometry of these filaments, map out the 3-dimensional structure of the remnant shell in this region, and derive better limits on the ambient gas density and its variation.

Mixed in with all of the Balmer-dominated filaments are two knots of radiative shock emission, labeled W1r. These knots were noted by Hill (labeled “B” in Hill 1967), but as with the northern radiative filaments, no spectroscopic observations of them have ever been published.

Finally, there are many extremely low level, diffuse structures within the boundaries of RCW 86. These have H α surface brightnesses of $\sim 3 - 6 \times 10^{-17} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ arcsec}^{-2}$, still well above the surface brightness limit of the mosaic ($\sim 1 \times 10^{-17} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ arcsec}^{-2}$). Perhaps the most interesting of these is a large triangular structure near the center of the remnant. This could simply be background (or foreground) diffuse H α emission, or it could be the front or back side of RCW 86. If it is the latter, deep spectroscopy could provide yet more 3D information about the remnant. A similar structure shows up at very low level in the [S II] image, implying that this faint central emission is not Balmer-dominated emission.

4. Radio and X-ray comparison

The optical shell of RCW 86, as defined by the newly discovered Balmer-dominated filaments, provides a more complete basis for comparison with the radio and X-ray images. While detailed comparisons await our upcoming high-resolution observations at radio (with the ATCA) and X-ray (pending ROSAT HRI observations) wavelengths, we have obtained existing radio and X-ray images in order to present a preliminary comparison here. In Fig. 6 we show a ROSAT PSPC image (observation RP500078A02), which has a resolution of approximately $30''$, and the 843 MHz radio image of Kesteven & Caswell (1987), with a resolution of $\sim 45''$, alongside our continuum-subtracted H α image. The global structure at the three wavelengths is similar, although several interesting differences are apparent.

As previously noted, the radiative filaments in the southwest coincide in all three bands,

although in this comparison one can see that the radio shows less of the knee shaped structure seen in both the optical and X-ray images. Radio (Hill 1967), X-ray (Pisarski, Helfand, & Kahn 1984, Claas et al. 1989), optical (Ruiz 1981, Leibowitz & Danziger, Rosado et al. 1996), and infra-red (Greidanus & Strom 1990) studies all agree that this bright feature has been produced by the SNR shock front encountering a dense cloud. The interaction is thought to be relatively recent because while observations indicate that the shock has been significantly decelerated in this region (from the ~ 600 to 800 km s^{-1} found in the northern filaments by Long & Blair 1990 down to $\sim 100 \text{ km s}^{-1}$ in the southwest, as measured by Rosado et al. 1996), the complex is at roughly the same distance from the center as the rest of the shell.

The eastern rim of the remnant also shows overall agreement at all three wavelengths. The sharp outer Balmer filaments of E2 seem to bound the radio and X-ray emission, but given the resolution of these radio and X-ray images, we are unable to measure any offset. The radio shows a definite filament branching off to the interior, corresponding to the E1 filament in $\text{H}\alpha$, and a corresponding feature in the X-ray appears to be present at a low level.

Moving north and west along the shell, the agreement between the three images breaks down somewhat along the northern rim. The X-ray image shows a distinct break in the northeast, which is accompanied by both a break in the optical filaments and an optical filament just beyond the break, suggestive of a mini-blowout at this location. The radio image shows no corresponding blowout, but just beyond that position it splits into a lower filament, which corresponds to the optical N1 complex as well as the X-ray bright rim, and an upper filament. The upper portion of radio emission forms a “northern cap”, which extends out beyond the N2 filaments seen in the optical. Some evidence of the northern cap is also seen in the X-ray image, although at a very faint level. The overall structure of the region, including the broken optical morphology of both the N1 and N2 optical filament complexes and the extension of the northern cap outside of the brightest filaments of radio and X-ray (corresponding to N1), is suggestive of a “captured blowout”, in which the shock has rushed out beyond the average expansion radius of the remnant (possibly defined by the N1 filaments), only to encounter a denser region. It is, however, puzzling that the northernmost edge, as defined by the radio and X-ray, shows no detected optical emission.

The complex western region shows some of the most striking differences between the three images. While faint optical filaments and the radio trace out the outer shock front W3b, there is little corresponding X-ray emission in the region. The X-ray emission is strongest along W2, which shows no radio counterpart, and fills the area between the W2 and W1 complexes. A faint radio filament seems to correspond to the inner filament W1, looping over to connect to W3 across the top of the region between W1 and W2 filled by both X-ray and Balmer emission.

Perhaps the most striking difference between the three images is the radio filament stretching across the southern portion of RCW 86. While both optical and X-ray filaments lie along the southwestern portion of this arc, they both fade out, leaving only the radio to trace out what appears to be a feature crossing the southern face of the remnant. This does not appear to be

the true southern extent of the remnant, as there is faint radio and X-ray emission outside of this feature in the southeast.

5. The Overall Picture, Distance, and Progenitor of RCW 86

The radio, X-ray and new optical images provide the general impression of RCW 86 as a SNR expanding into a very inhomogeneous medium. To the southwest the blast wave has encountered a rather large, dense cloud, and to the north it has encountered smaller scale density enhancements embedded in a low-density partially neutral medium, as demonstrated by the mixture of radiative and Balmer-dominated filaments observed there. On the east and west sides the remnant is expanding into rather low-density, partially neutral gas, but the relatively bright X-ray filaments on the west side seem to imply some significant variations in the conditions even in that region.

These variations in the surrounding ISM are perhaps not surprising, given the projected location of RCW 86 relatively close to the Galactic plane ($l=315.4$, $b=-2.3$; the Galactic plane lies to the north-northwest of the remnant). Its actual distance off of the Galactic plane is, of course, dependent on the distance to the SNR, the value of which has been the subject of much debate in the literature. All recent X-ray analyses derive distances of ~ 1 kpc, while most of the other estimates range from 2.3 to 3.2 kpc. While many of the X-ray studies have assumed an age of 1800 years (corresponding to the assumption that the remnant is the result of SN 185), Nugent et al. (1984) and Leahy (1996) do not base their analyses on this assumption and nevertheless derive distances of ~ 0.7 kpc and 1.6 kpc, respectively.

The larger distance estimates are based on the Σ -D relation, the possible link between the SNR and an OB association, a kinematic distance, or the measured optical extinction. In the radio, there are no published H I absorption distance estimates, so the only estimates available are based on the Σ -D relation. However, as mentioned in the introduction, Σ -D is extremely unreliable (Green 1991), with uncertainties which could place RCW 86 at a distance of anywhere between 1 and 10 kpc (Strom 1994).

One of the oldest, and possibly most influential, distance estimates is the suggestion of a link between RCW 86 and an OB association found along the line of sight. Westerlund (1969) proposed this link based upon the projected proximity of several OB stars, the rough agreement between the radial velocities of the filaments ($+1$ and $+27$ km s $^{-1}$) and the stars (between -14 to $+20$ km s $^{-1}$), and the assumption that the remnant was of a Type II supernova. However, the majority of recent X-ray analyses find that a Type Ia progenitor is favored by the models (Pisarski, Helfand, & Kahn 1984, Claas et al. 1989, Leahy 1996; see however Kaastra et al. 1992), although a Type II SN cannot be ruled out. Also, recent Fabry-Perot measurements of the bright filaments in the bright southwestern knee of RCW 86 by Rosado et al. (1996) give a V_{LSR} of -33.2 ± 4.5 km s $^{-1}$, seemingly inconsistent with the reported stellar velocities (although it is not clear if those velocities were corrected to V_{LSR}). Rosado et al. continue on to derive a kinematic

distance for RCW 86 of 2.8 ± 0.4 kpc, but this estimate is again based upon the assumption that the progenitor SN was of Type II (as they point out), and therefore neither defines the SN type nor provides an unambiguous distance.

Large values of optical extinction have also been pointed to in support of larger distances. Leibowitz & Danziger (1983) derived a value of $A_V = 1.7$ mag from spectra of various bright filaments of the southwestern knee. As they point out, this value is consistent with the A_V of 2 measured for the OB association (Westerlund 1969). However, these values seem at odds with the absorption derived from various X-ray measurements, which have consistently yielded column densities of approximately $1 - 2 \times 10^{21} \text{ cm}^{-2}$ or less (Nugent et al. 1984, Pisarski, Helfand, & Kahn 1984, Claas et al. 1989, Kaastra et al. 1992, Leahy 1996, Vink, Kaastra, & Bleeker 1997). If we take the simplest conversion provided by Burnstein & Heiles (1978, eq. 7), we obtain an $E(B - V)$ of ~ 0.15 , or an A_V of ~ 0.5 . Indeed, Leibowitz & Danziger’s own extinction data show significant scatter, including at least one very low value which they attribute to a hole in the foreground material. As Strom (1994) suggests, the scatter in the optical extinction may equally well be attributable to absorption in or near the filaments, due to the significant amount of dust evident (Greidanus & Strom 1990) where the optical extinction was measured. Optical measurements of the radiative filaments in the north, away from the large dense cloud in the southwest, may provide better estimates of the true optical extinction.

The large distance estimates, and the corresponding apparent relation to the OB association, have recently been used as arguments against the hypothesis that RCW 86 is the remnant of SN 185 (Thorsett 1992, Schaefer 1995, Rosado et al. 1996). However, the smaller distance of ~ 1 kpc is certainly not ruled out by existing observations, and may even be favored over the larger distance estimates, despite the claims to the contrary published since Strom’s (1994) review, which favored the smaller distance and argued that RCW 86 is the most likely remnant of SN 185. Finally, while the lack of proper motion in the bright southwestern filaments reported by Kamper, van den Bergh, & Westerlund (1995) was said to contradict the youth of RCW 86, it fails to constrain the overall expansion of the remnant. As pointed out above, the shock has been slowed by almost an order of magnitude in this region (as compared to the northern rim), and thus would not be expected to have the large proper motion characteristic of a young, nearby remnant. On the other hand, the proper motion of the Balmer-dominated filaments should provide an accurate measurement of the expansion rate, and when combined with a shock velocity determined from spectroscopy of the same filaments, should provide an accurate estimate of the distance (e.g., Long, Blair, & van den Bergh 1988, Smith et al. 1991).

Further observations, especially of these newly identified Balmer-dominated filaments, will certainly shed further light on the distance to, and perhaps the progenitor of, SNR RCW 86. Low resolution spectroscopic data for the northern radiative filaments could yield independent optical reddening estimates (away from the apparently dense cloud in the SW), while moderate resolution spectra can provide shock velocities and angles to the line of sight for most of the Balmer-filaments. High-resolution spectra of the Balmer filaments would also give a more precise

measurement of the systemic velocity than that of Rosado et al. (1996), since the line center of the narrow component provides an accurate measurement of the preshock gas conditions independent of the angle to our line of sight. And in the near future, we should be able measure the proper motion of the Balmer-dominated filaments, finally giving an accurate distance to the SNR. When combined with detailed X-ray spectroscopy (e.g., Hughes et al. 1995), these measurements should shed light on whether RCW 86 is an older relative of SN 1006, with a Type Ia progenitor, or a younger version of the Cygnus Loop (a Type II cavity explosion? See Vink, Kaastra, & Bleeker 1997) which we have caught before significant portions of the shell have begun to develop radiative shocks.

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Table 1. Journal of Optical Imaging with Curtis Schmidt

Field	RA(2000)	Dec(2000)	Date (UT)	H α	[S II]	Red
NE	14:44:00	-62:18:00	1994 Mar 23	5 \times 600s	3 \times 600s	4 \times 300s
NW	14:40:45	-62:18:30	1994 Mar 24	6 \times 600s	4 \times 600s	4 \times 300s
SE	14:44:00	-62:36:00	1994 Mar 23	5 \times 600s	3 \times 600s	3 \times 300s
SW	14:41:08	-62:32:00	1994 Mar 24	4 \times 600s	3 \times 600s	4 \times 300s
NE	14:44:02	-62:18:15	1995 Jan 26	3 \times 600s	...	3 \times 300s
NW	14:40:39	-62:18:34	1995 Jan 27	3 \times 600s	...	3 \times 300s
SE	14:44:00	-62:36:15	1995 Jan 29	4 \times 600s	...	2 \times 300s
SW	14:40:38	-62:37:24	1995 Jan 28	3 \times 600s	...	2 \times 300s
Center	14:41:35	-62:32:06	1995 Jan 28	2 \times 600s	...	2 \times 200s

Fig. 1.— The $H\alpha$ image mosaic of the supernova remnant RCW 86. The image is $46'.8$ square, covering the entire area of the X-ray and radio shells, with N up and E to the left. The bright radiative filaments are immediately apparent. While some of the fainter filaments are also noticeable, it is difficult to judge their extent due to the stellar confusion in this region projected so near the Galactic plane.

Fig. 2.— The continuum-subtracted $H\alpha$ mosaic of RCW 86, showing the wealth of faint Balmer filaments stretching almost completely around the remnant, as well as faint diffuse $H\alpha$ emission in the center. Most of the “noise” seen in this image is from the wings of subtracted stars.

Fig. 3.— The final $H\alpha$ mosaic RCW 86, which has been median filtered to suppress the remains of most of the subtracted stars.

Fig. 4.— The final median-filtered, continuum-subtracted $[S\ II]$ mosaic of RCW 86, clearly showing the locations of the radiative filaments.

Fig. 5.— The final $H\alpha$ image mosaic of RCW 86 with various filament complexes identified for reference. The labels run from the center of the remnant outward, so that smaller numbers correspond to smaller projected distances from the center of the remnant. Where needed, suffixes are used to distinguish the Balmer-dominated filaments (“b”) from the radiative filaments (“r”).

Fig. 6.— A comparison of RCW 86 (a) in X-rays, as seen with ROSAT PSPC, (b) in the optical in $H\alpha$ emission, and (c) in the radio at 847 MHz.

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